THERMAL MANAGEMENT SYSTEM AND METHOD FOR VEHICLE ELECTROCHEMICAL ENGINE

FIELD OF THE INVENTION

[0001] This invention relates to the field of thermal management and in particular, a thermal management system and method for an electrochemical engine used in a vehicle.

BACKGROUND OF THE INVENTION

[0002] Thermal management of an electrochemical engine presents several important considerations and challenges as compared to a conventional internal combustion engine. First, in an internal combustion engine, waste heat is managed about equally through both an exhaust gas stream and through a flow of air-cooled engine coolant. In comparison, an electrochemical engine manages most of its waste heat through air-cooled engine coolant. Second, an internal combustion engine typically operates at 120°C, where an electrochemical engine operates at the lower temperature of 80°C. Therefore, the heat transfer between the coolant and air in a thermal management system of an electrochemical engine is about one-half that of an internal combustion engine due to the smaller temperature differential between the waste heat and ambient at 38°C. These two considerations in combination may necessitate a threefold increase in the cooling airflow rate through the radiator and an order of magnitude increase in its associated fan power.

[0003] The cooling requirement has generally been met by placing a large radiator at the front of the vehicle. However, due to the current size of the radiator, vehicle style has been strongly driven by the high rate of airflow required for cooling. Although some reduction of heat rejection requirements is achieved through higher thermodynamic efficiencies of the electrochemical engine, there is a continued need for creative cooling solutions for vehicle applications where space is limited.

SUMMARY OF THE INVENTION

[0004] This invention greatly reduces the required cooling airflow rate by including the heat of water vaporization. The reduced airflow rate is accommodated in a much smaller, and therefore more easily packaged radiator by including evaporative cooling.

[0005] In one embodiment, a method of managing heat from an engine for a vehicle is provided. The method comprises providing airflow over a surface of a heat exchanger circulating coolant used to cool the engine. The airflow is used to reject heat from the heat exchanger. The method further includes wicking water over the heat exchanger to supplement the cooling capacity of the airflow by evaporative cooling.

[0006] In another embodiment, a thermal management system of an engine for a vehicle is provided. The system comprises a coolant pump, a radiator comprising a wicking mechanism and an associated fan to provide airflow over the wicking mechanism. The system includes a coolant circuit circulating coolant used to cool the engine. The coolant circuit fluidly connects the engine, the coolant pump, and radiator. A supply of water is in fluid connection with the wicking mechanism to supplement the cooling capacity of the airflow by evaporative cooling.

[0007] These and other features and advantages of the invention will be more fully understood from the following description of preferred embodiments of the invention taken together with the accompanying drawings. It is noted that the scope of the claims is defined by the recitations therein and not by the specific discussion of features and advantages set forth in the present description.

BRIEF DESCRIPTION OF THE FIGURES

[0008] The following detailed description of the embodiments of the present invention can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

[0009] FIG. 1 is a schematic layout depicting an engine embodying the present invention;

[0010] FIG. 2 is a graph of cooling effectiveness and quantity of water for evaporative cooling according to the present invention;

[0011] FIG. 3 is a schematic section view of a radiator with non-evaporative and evaporative cooling regions according to an embodiment of the present invention; and

[0012] FIG. 4 is a schematic top view of a vehicle embodying an engine and associated thermal management system of the present invention.

DETIALED DESCRIPTION OF THE EMBODIMENTS OF THE INVENTION

[0013] With reference to FIG. 1, an engine is generally indicated by symbol 10. In one embodiment, the engine 10 is an electrochemical engine (ECE), which operates to generate electricity in a fuel cell stack given two reactants, e.g., a hydrogenous gas and a gas containing oxygen. Hydrogenous gases for the fuel cell stack may be produced on board the vehicle and this method is described hereinafter; however, the present invention is not limited to such a system. In another embodiment, the engine 10 is a conventional internal combustion (IC) engine for vehicles that have limited radiator space.

[0014] In the illustrated embodiment, a liquid fuel, such as gasoline, diesel, methanol, etc., is stored on board the vehicle in a fuel tank 12. The fuel is supplied to a fuel processor 14 in the ECE 10. The fuel processor 14 may also receive compressed air from an air compressor 16 for partial oxidation and water, if available, from a water tank 18 for steam reformation. A combustor 20 generates and supplies heat to the fuel processor 14, wherein the fuel processor partially oxidizes and reforms the fuel to produce a hydrogen-containing reformate. If water is available, the fuel processor 14 steam reforms a portion of the fuel to produce additional hydrogen. Having water present also reduces the likelihood that methane and solid by-products such as soot and carbon are created.

[0015] To reduce residual carbon monoxide in the reformate, the fuel processor 14 may further include one or more carbon monoxide reduction reactors where the residual carbon monoxide is combined with water to produce carbon dioxide and hydrogen. The fuel processor 14 may further include a carbon monoxide cleanup reactor where the residual carbon monoxide is oxidized using air from the air compressor 16. The reformate also may be passed through a cooler, if cooling is necessary before the reformate is delivered to a fuel cell stack 22.

[0016] To generate electricity in the fuel cell stack 22, the hydrogen-containing reformate is delivered under pressure to the stack. The fuel cell stack 22 contains a series of individual bipolar fuel cell plates 24, as is known in the art. The hydrogen-containing gas is fed through an anode, not shown, to create positively charged hydrogen ions. Concurrently the air compressor 16 and an optional cathode humidifier 26 provide a humidified oxidant supply to a cathode, not shown, of the fuel cell plates 24. The cathode is separated from the anode by an electrolyte. If a humidifier 26 is used, it may receive water from the water tank 18. Electricity is generated in the fuel cell stack 22 by electrochemically processing the hydrogen and oxygen in a manner known in the art. The generated electricity may power a drive system and auxiliary vehicle devices.

[0017] As an alternative to reforming hydrogen on-board as described above, hydrogen for the electrochemical process may be stored on-board the vehicle in a suitable storage tank. The hydrogen may be stored either in its gaseous state, liquid state, or in a captured solid state by a hydrogen-retention material contained within the storage tank. Hydrogen-retention material refers to a material, which is capable of reversibly taking-up and storing hydrogen at a storage temperature, and releasing it at a release temperature, which is greater than the storage temperature. Examples of hydrogen retention material include metals such as sodium-aluminum, lanthanum-nickelide, titanium, or nickel, which react with and store the hydrogen as a hydride of the metal.

[0018] Depending on the initial liquid fuel, the fuel cell stack 22 may exhaust methane, unconsumed hydrogen, carbon dioxide, nitrogen, and water from the anode and

unconsumed oxygen, nitrogen, and water from the cathode. In addition to the above-described exhaust gases, the fuel cell stack 22 also generates heat. To manage the heat, the ECE 10 includes a thermal management system 28 comprising a coolant pump 29, a primary coolant circuit 30 to circulate low temperature engine coolant through the fuel cell stack 22, transferring waste heat out of the stack. The heated coolant is cooled through a heat exchanger, such as an air-cooled radiator 32, which may have an associated fan 35 to fòrce air from an air duct (not shown) through the radiator. The thermal management system 28 further includes a condenser 34 for reclaiming water from the wet exhaust of the fuel cell stack 22, the water tank 18 for storing the reclaimed water, and a water pump 36.

[0019] Water is reclaimed in the ECE 10 by routing the exhaust streams from the fuel cell stack 22 through the combustor 20, which provides the dual function of consuming undesirable exhaust components and generating heat for the fuel processor 14. In one embodiment, the wet exhaust stream flowing out of the combustor 20 is directed through the condenser 34 to reclaim liquid water before finally being exhausted from the vehicle in one embodiment. In an alternative embodiment, the exhaust stream from the fuel cell stack 22 may be first routed through the condenser 34 and then to the combustor 20 before exiting the vehicle.

[0020] In still another embodiment, as a means for trying to keep the water tank 18 above freezing (i.e., > 0°C) to minimize the risk of potentially damaging the water pump 36, the exhaust or coolant may be operatively directed to flow through the water tank 18 when the temperature is around or below freezing. Additionally, the exhaust gas or coolant flow may be used to thaw critical portions of the water tank and supply lines under the sub-zero ambient conditions when the water tank 18 may have become frozen. As used herein, the terms "operatively directed" and "operatively directing" mean that an actuated value or other system connecting means is controlled by a controller monitoring internal and external conditions of the ECE 10 and effectuating the indicated system arrangement given the indicated (sensed) condition. As using controllers for this purpose is well know in the art, no further discussion is provided. Additionally, it is to be

appreciated that in the embodiment using coolant, the coolant may be continuously directed to flow through the water tank 18 even when temperatures are above or below freezing.

[0021] Optionally, a small resistive element 38 may be provided either to the walls of the water tank 18 or through the walls to the water itself, where a small current may be drawn from a battery even when the ECE 10 is not operating to prevent the water in the tank from freezing. In still other embodiment, the conventional cooling capacity of the radiator 32 is sized to provide adequate heat rejection under these cold weather conditions such that water in tank 18 need not be stored, and the associated freeze challenges would be avoided.

[0022] To maintain sufficient water levels in tank 18, under normal operating conditions, and whenever the radiator 32 has additional cooling capacity, either a portion or all of the wet exhaust from the combustor may be operatively directed through the condenser 34 for condensing water and filling water tank 18 with reclaimed water. Such an arrangement would be beneficial where the water tank 18 is provided as a separate storage tank than that used to provide water to fuel processor 14 and/or humidifier 26. Optionally, the water tank 18 could also be refilled at the same interval, at the same time, and at the same filling station as the fuel tank 12.

[0023] Returning now to the discussion of the thermal management system 28, water is supplied in the following manner. From the water tank 18, the reclaimed water is pumped to the fuel processor 14 upon ECE start-up and during normal ECE operation to improve the engine efficiency, as processing the fuel with water releases more hydrogen than processing the fuel with only air. Optionally, and depending on the configuration of the fuel cell stack 22, water from the water tank 18 may also be operatively directed from the pump 36 to the humidifier 26 to humidify the air input to the anode and/or cathode.

[0024] Additionally, under peak power or hot day conditions when the cooling capacity of the radiator 32 is not sufficient, the reclaimed water is used to supplement the cooling

capacity of the radiator by operatively directing water from the tank 18 to the radiator 32 via pump 36. It is to be appreciated that the cooling capacity of the airflow is increased by including evaporative cooling of water into the airflow. To ensure full utilization of the water for evaporative cooling, the reclaimed water is introduced through a wicking mechanism 33 disposed on the exterior surface of the radiator 32, and in particular on the fins. Suitable wicking mechanism 33, include but not limited to, capillary wicking structures such as for example fibers, felts, foams, weaves, and wicking materials, such as for example metals (preferred for thermal conductivity), polymers selected for hydrophilic surface properties or pyrolized organics with hydrophilic surface properties.

[0025] An alternate approach to enhance cooling, especially for the embodiments where the engine 10 is an IC engine, is to spray all or a portion of the water supplied by the pump 36 onto the radiator 32. In this alternative embodiment, cooling effectiveness of the radiator 32 is about 80-85%. Additionally, by using the wicking mechanism 33 as part of the radiator 32, water loss from droplets passing through the radiator is substantially avoided.

[0026] By evaporatively cooling the exterior surface of the radiator 32, the reclaimed water need not be as pure if used to evaporatively cool a fuel cell internally where ions could contaminate the membrane. Further, any scale deposits left by the evaporated water is more readily cleaned from the exposed surfaces of the radiator 32 than from the interior of the fuel cell stack 22.

[0027] It is to be appreciated that the present invention significantly enhances the cooling capacity of the cooling air used to reject heat from an electrochemical engine by adding liquid water to the heat rejection device to utilize the heat of vaporization. FIG. 2 shows a graph illustrating the ratio of effective heat capacities with evaporative cooling to without evaporative cooling as illustrated by the line indicated by symbol B. The ratio of effective heat capacities being the heat rejection ratio for the same mass flow of air for the same temperature rise. The chart also provides the ratio of water to airflow on a mass basis as illustrated by the line indicated by symbol A. This calculation assumes that the

air exiting the heat rejection device is saturated by water vapor at the temperature indicated. For example, at an exit temperature of 80°C, the effective heat capacity is about 27x larger (so 27x less cooling airflow is required), and a water flow of only 0.5 times the airflow is required.

[0028] In the illustrative embodiment of FIG. 3, the radiator 32 comprises engine coolant passages 40, and fins 42 on the airside. In one embodiment, each fin 42 has or is the wicking mechanism 33, which is capable of wicking water provided from a water supply, such as water tank 18, over the heat rejection surface of the radiator 32. In another embodiment, and when ambient temperatures vary between sub-zero and warm weather conditions (i.e., > 0°C), for sub-zero operations a forward portion of fins 42 would not include the wicking mechanism 33 as the cold ambient temperatures would freeze the water used for evaporative cooling. In such an embodiment, after the cooling air warms above freezing as it passes through the forward portion of the radiator 32, evaporative cooling is then used in a warmer rearward portion of the fins and/or radiator having the wicking mechanism 33 to maximize the benefit of evaporative cooling on radiator size and cooling airflow requirements.

[0029] In still another embodiment, the radiator 32 has wicked cooling zones wherein water is operatively directed to forward and rearward wicking mechanism portions of the radiator 32 during warm weather conditions and to only the rear wicking mechanism portion during freezing weather conditions. The forward wicking mechanism portion comprises the wicking material and/or structure on the airside portion of the fins 42. The rearward wicking mechanism portion also comprises the wicking material and/or structure on the aft portion of the fins and/or radiator. The location of the rearward wicking mechanism is such that under normal operating condition of the electrochemical engine, the rearward wicking mechanism experiences above freezing temperatures due to heat transfer from the circulating coolant, even when the vehicle is subject to near freezing temperatures (i.e., 0 to 5° C) and below. The forward and rearward wicking mechanism portions are supplied with water from the water tank 18 via pump 36, through separately controlled rewetting arteries.

[0030] It is to be appreciated that the quantity of water that needs to be stored will scale with the quantity of on-board fuel and engine efficiency (and exhaust heat rejection). The heat generation rate of the electrochemical engine is calculated by the following Equation (1):

$$Q = N*(1.25 - V)*I \qquad (1)$$

where Q is the heat generated, N is the number of cells, V is the cell voltage, I is the cell current. For example, if all of the heat rejection is handled by water vaporization, for an average cell operation of 0.75 volts, the quantity of water that needs to be stored is 20x the mass of stored hydrogen as current is proportional to hydrogen flow.

[0031] Turning now to FIG. 4, a schematic plan view of a vehicle 44 embodying an electrochemical engine 10 with the associated radiator 32 located forward of a front axle 46 of the vehicle is illustrated. In an alternative embodiment, the radiator 32 may be located behind a rear axle 48 of the vehicle 44. Fuel is stored in the fuel tank(s) 12, shown here in the rear underbody compartment of the vehicle forward of the rear axle 48 of the vehicle 44. The rear underbody compartment is defined by the volume between frame rails 50, 52 forward of the rear axle 48 and below the vehicle floor 54.

[0032] In the illustrated embodiment, the water tank(s) 18 enclose the fuel tank(s) 12 to utilize the void spaces associated with the fuel tank(s). For example, in the embodiment where storage hydrogen is used, it is to be appreciated that the storage of hydrogen for vehicles is generally accomplished by storing hydrogen as compressed gas in high-pressure cylinders. Accordingly, the volume around these cylinders is of an odd shape and generally not useful for other components. In such an embodiment, adequate evaporative cooling water could be stored in these void spaces, by for example, using cylinders having a 30-liter internal volume (27.6 cm diameter by 75 cm long). In such an example, the rectangular volume enclosing these cylinders would provide 29x more water storage than the internal hydrogen storage on a mass basis for hydrogen storage at 250 bar pressure. Such water storage capacity exceeds the illustrated 20x the mass of stored

hydrogen, if all of the heat rejection is handled by water vaporization, for an average cell operation of 0.75 volts.

[0033] While the invention has been described by reference to certain preferred embodiments, it should be understood that numerous changes could be made within the spirit and scope of the inventive concepts described. Accordingly, it is intended that the invention not be limited to the disclosed embodiments, but that it have the full scope permitted by the language of the following claims.